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# Numerical Prediction of Precipitation and River Flow over the Russian River Watershed during the January 1995 California Storms

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## ABSTRACT

Precipitation and river flow during a January 1995 flood event over the Russian River watershed in the northern Coastal Range of California were simulated using the University of California Lawrence Livermore National Laboratory's Coupled Atmosphere–River Flow Simulation (CARS) System. The CARS System unidirectionally links a primitive equation atmospheric mesoscale model to a physically based, fully distributed hydrologic model by employing an automated land analysis system. Using twice-daily National Meteorological Center eta model initial data to provide the large-scale forcing to the mesoscale model, the CARS System has closely simulated the observed river flow during the flooding stage, where the simulated river flow was within 10% of the observed river flow at the Hopland gauge station on the Russian River.

## 1. Introduction

Predicting local precipitation, land surface hydrology, and river flow is important for early flood warnings and for efficient management of reservoirs. In mountainous areas such as the western United States, steep terrain and narrow valleys can cause severe flooding during heavy precipitation events. To prevent flooding, local reservoirs need to release stored water when heavy precipitation is expected. Therefore, inaccurate predictions of local precipitation and river flow can cause either unexpected flooding or unnecessary releases of water resources.

As part of an effort to investigate regional-scale atmospheric flows, precipitation, surface hydrology, and river flow at various temporal scales, we have developed a Coupled Atmosphere–River Flow Simulation (CARS) System. This modeling system can be used to forecast or diagnose both atmospheric conditions and land surface hydrology on regional to catchment scales. We applied the CARS System to a preliminary numerical prediction study over the Russian River Basin in the northern California Coastal Range during a flooding period in early January 1995. The following sections discuss the CARS System and the simulated precipitation and river flow.

## 2. The Coupled Atmosphere–River Flow Simulation System

The CARS System consists of three unidirectionally coupled numerical models: 1) the Mesoscale Atmospheric Simulation (MAS) Model, 2) the Automated Land Analysis System (ALAS), and 3) a modified version of the hydrology model known as TOPMODEL. As illustrated in Fig. 1, the CARS System can be nested within either a large-scale forecast or analysis data. Hence, the CARS System may be employed for predictions of regional weather and river flow or for simulating regional climatology, depending on the choice of the large-scale input data.

The unidirectional coupling occurs as follows. The MAS model simulates precipitation and atmospheric variables at a 20-km horizontal resolution using initial and time-dependent lateral boundary conditions

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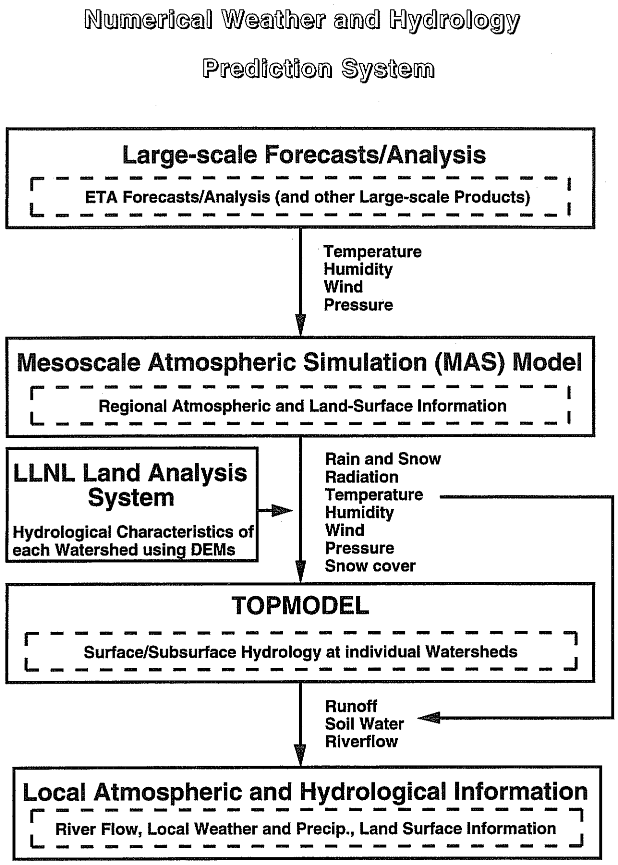


FIG. 1. Nesting procedure of the CARS System.

obtained from large-scale atmospheric input data. The simulated precipitation and atmospheric variables are then averaged over individual watershed areas computed by ALAS. TOPMODEL computes river flow using the watershed area mean precipitation and atmospheric variables simulated by MAS in conjunction with surface properties provided by ALAS.

The MAS model (Kim and Soong 1994) is a primitive equation, limited-area mesoscale model, which includes a third-order-accurate advection scheme (Takacs 1985) and physical processes for 1) precipitation and thermal forcing due to deep convective clouds and stratiform clouds, 2) solar and terrestrial radiative transfer within the atmosphere, and 3) turbulent transfer at the earth's surface and within the atmosphere. MAS directly computes rainfall and snowfall separately using a bulk cloud microphysics scheme by Cho et al. (1989). It also provides mixing ratios of cloud water and cloud ice that are used to determine optical properties of water- and ice-phase clouds for computing solar and terrestrial radiative transfer. Interactions between the atmosphere and land surface are computed using the Coupled Atmosphere–Plant-Snow Model (Mahrt and Pan 1984), which has been fully coupled to MAS and has enabled us to keep track of available water resources, including those stored in the snowpack.

The Automated Land Analysis System is based on software developed by the United States Geological Survey (Jenson and Dominque 1988) and the Lawrence Livermore National Laboratory (Miller 1995). ALAS provides information on topographic properties such as river networks, watershed areas, and hydrologic characteristics at specified resolutions using digital elevation model data. The area and location of watersheds determined by ALAS are matched to the grid points of the MAS model, so that computed watershed area mean atmospheric variables and precipitation are available to TOPMODEL as input.

TOPMODEL is a physically based, fully distributed hydrology model. The conceptual version of TOPMODEL was initiated by Kirkby (1975), and the numerical model was developed by Beven and Kirkby (1979). TOPMODEL computes the soil water budget, surface–subsurface flow, and the volume of routed river flow in a specified area. It has been improved to include the effects of spatial scale on hydrologic processes (Sivapalan et al. 1990; Beven et al. 1988; Wood et al. 1990) and has been applied to many surface hydrological studies, including the effects of terrain on streamflow (Beven and Wood 1983) and the effect of climate change on hydrological processes (Wolock and Hornberger 1991). Our version of TOPMODEL has been further modified in that it is driven by atmospheric variables (precipitation, temperature, winds, and radiation) provided by the MAS model.

## 3. Precipitation and river flow simulations over the Russian River Basin

During January 1995, California received an unusually large amount of precipitation. Between 7 and 11 January, three consecutive, strong storms hit California. Several parts of the state were affected by high water, as the soils became saturated when the second storm reached the area. The Russian River Basin was among the areas hardest hit with an estimated flood-related damage of over $800 million. We carried out a simulation of local precipitation and river flow during a flooding episode along the Russian River Basin in the northern California Coastal Range.

River flow simulations require separate inputs for rainfall and snowfall, since snowfall does not immediately affect river flows. The simulated 24-h accumulated rainfall and snowfall over the southwestern United States on 10 January 1995 are shown in Figs. 2a,b. The MAS model predicted heavy rainfall during this period along the northern Coastal Range, the western slope of the Sierra Nevada, and the southern California coast near Santa Barbara, which was also severely flooded. Rainfall to the north of the San Francisco Bay, including the northern part of the Russian River Basin, was particularly heavy. Since the snow line was located at approximately 2000 m (Fig. 2b), all of the precipitation that fell over the Russian River Basin was in the form of rain, which quickly saturated the soils and caused overland flooding.

Orographic features of the terrain in California cause strong spatial gradients in precipitation. To illustrate the importance of accurate estimations of local precipitation for computing river flows within mountainous terrain, we computed area mean daily precipitation over the entire Russian River Basin (3425 $km^2$) and over the area within the Russian River Basin north of the Hopland gauge station (658 $km^2$) during the simulation period. The terrain of the entire Russian River watershed and an enlargement for the region of the Russian River watershed north of the Hopland gauge station (hereafter Hopland watershed) are shown in Fig. 3. The simulated daily precipitation averaged over the entire Russian River watershed and the Hopland watershed frequently differs by a factor of 2–3, especially during the flooding stage (Fig. 4).

Figure 5 compares the simulated 6-h accumulated precipitation averaged over the Hopland watershed to the observed area mean precipitation, which is used to run the operational river flow model of the California–Nevada River Forecast Center. These observed area mean precipitation data are based on four rain gauge values from Willits, Ukiah, Yorkville, and Lake Mendocino (Fig. 3). A weighting function based on climatological rainfall distribution within the Hopland watershed (E. Strem 1995, personal communication) gives observed area-averaged precipitation of these areas as

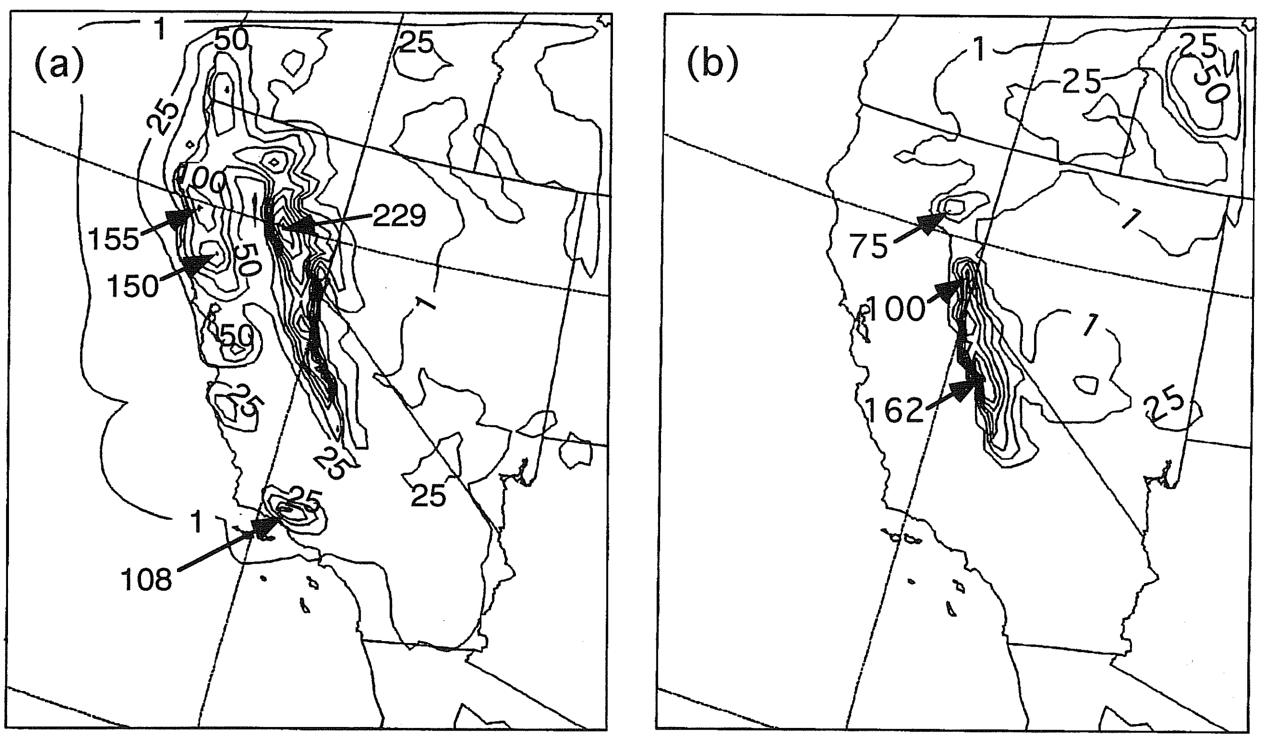


FIG. 2. A 24-h accumulated (a) rainfall and (b) snowfall, in equivalent water depth, forecasts for 0000 UTC 1 September–0000 UTC 1 October 1995 over the model domain. Units are in mm day$^{-1}$. The contour interval is 25 mm.

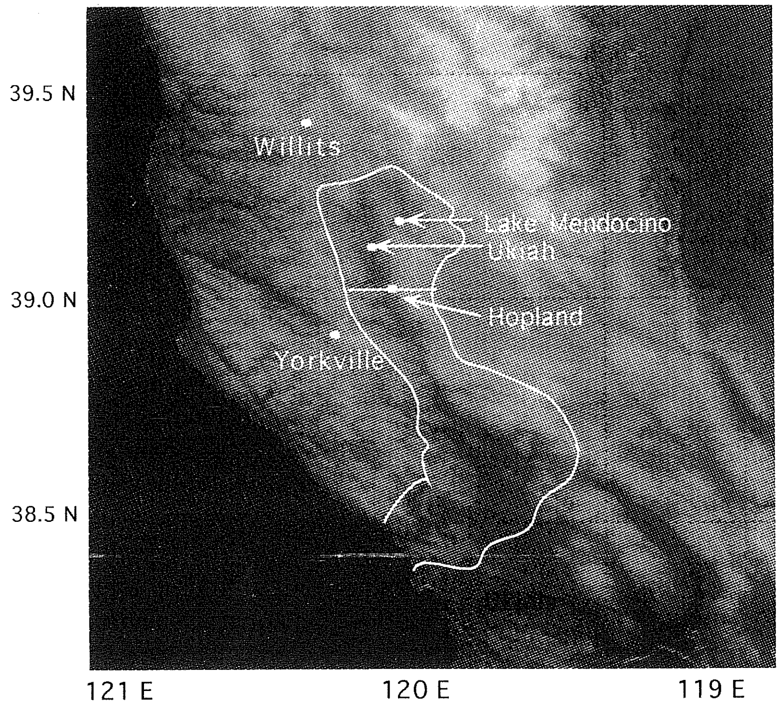


FIG. 3. Terrain and watershed boundary of the Russian River Basin at a 250-m resolution. The Hopland watershed is located north of the 39°N parallel (indicated by a solid east–west line at Hopland) within the Russian River Basin.

$$\overline{P}_{\text{Hopland}} = 0.22P_{\text{Willits}} + 0.28P_{\text{Ukiah}} + 0.23P_{\text{Yorkville}} + 0.28P_{\text{Lake Mendocino}},$$

where $\overline{P}$ and $P$ are area mean and single rain gauge values, respectively. The simulation has well captured the amount and timing of precipitation over the Hopland watershed during the study period, except on 10 January where the model significantly overestimated the observed precipitation. This overestimation was due to a large amount of moisture influx into the area prescribed by the eta model initial fields.

In this study, soil texture, topography, and the initial soil water saturation deficit were the most important surface properties for computing river flow. The initial soil water content for this simulation was obtained by running TOPMODEL with the observed climate history prior to the January 1995 storms. Watershed properties for the Hopland Basin were computed at a 200-m resolution using topographic elevation data at a 100-m resolution, as sensitivity studies indicated that this resolution is sufficient for the region.

Figure 6 illustrates the observed and simulated daily mean river flow volume at the Hopland gauge station from 1 to 12 January 1995. The CARS System simulated the river flow rate within 10% accuracy during the flood stage. A significant overestimation of the modeled river flow for 11 January was due to overpredicted rainfall on 10 January. The simulated river flow exceeded the observed river flow by approximately 30% during low flow periods before flooding mainly due to the uncertainties in the initial soil water content.

## 4. Conclusions

We have developed a Coupled Atmosphere–River Flow Simulation System by coupling a mesoscale atmospheric model with a physically based, distributed hydrologic model that simulates regional precipitation, mesoscale atmospheric circulations, surface hydrology, and river flow. This prototype system successfully modeled the January 1995 storms that caused severe flooding along the Russian River watershed in the northern California Coastal Range. The simulated area mean precipitation is in strong agreement with the observed precipitation. The simulated river flow is also in strong agreement with the observed value at the Hopland gauge station along the Russian River, as the simu-

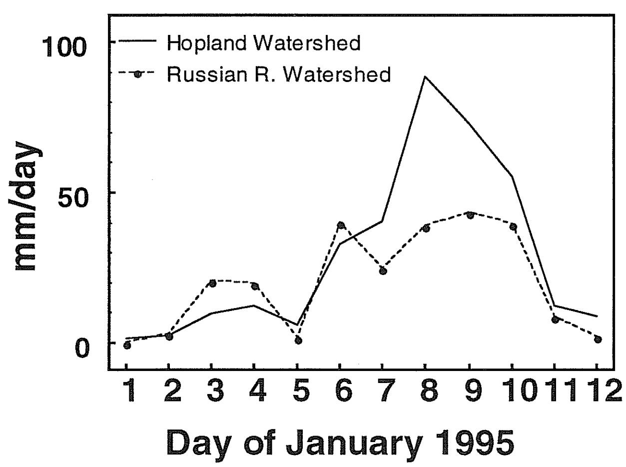


FIG. 4. The simulated area mean precipitation over the entire Russian River watershed (dashed line with solid circles) and over the Hopland watershed (solid line).

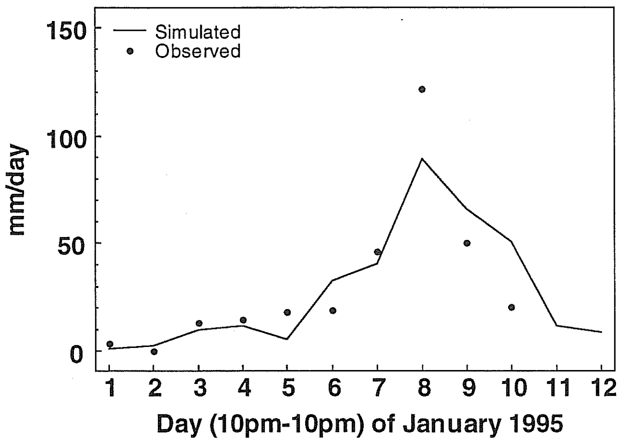


FIG. 5. The observed (circles) and simulated (line) area-averaged, 6-h accumulated precipitation over the Hopland watershed.

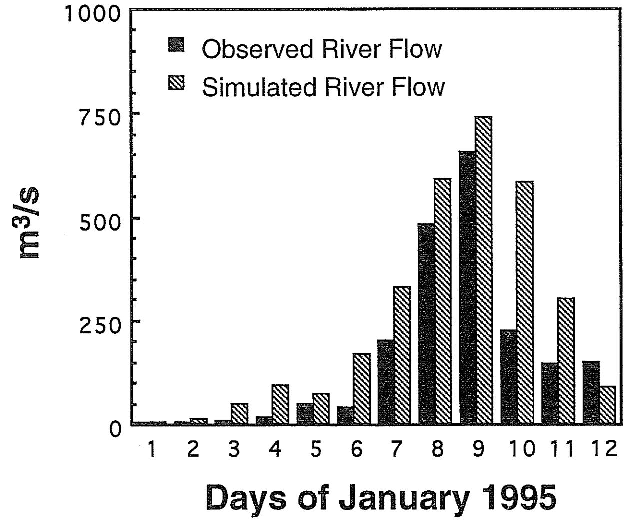


FIG. 6. The observed (solid bar) and simulated (shaded bar) river flow rate at the Hopland gauge station.

lated river flow during the flooding period differs from the observed value by 10%.

The CARS System is currently being employed for experimental numerical weather prediction for the southwestern United States. We have successfully run this system continuously from 1 January to 30 March with a similar accuracy level. These results are being prepared for a more detailed manuscript. The hydrologic simulation component of the CARS System is being extended to include several other major river systems within California, including the Lake Shasta inflow, the American River, and the Feather River.

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